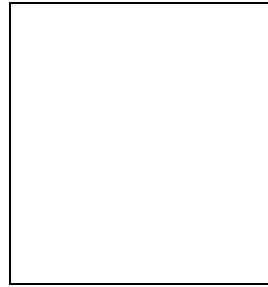


## GEONEUTRINO ANALYSIS IN KamLAND: INPUT AND DESIDERATA

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The Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND) is collecting antineutrino events generated by nuclear reactors and by Thorium and Uranium decay in the Earth interior. We comment on a systematic approach to the evaluation of the geo-neutrino contribution and of its uncertainties in KamLAND, taking into account geophysical and geochemical indications, estimates, and data. The results can help to improve both the neutrino oscillation analysis and the knowledge of the Earth interior. Input and desiderata for future geoneutrino analyses are identified.

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## 1 Introduction

The Earth surface radiates about 40 TW of heat. About 40% of this power energy ( $\sim 16$  TW) is believed to have radiogenic origin, mainly from  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  decays inside the crust and mantle of the Earth (see, e.g. <sup>1</sup>). The radiogenic heat is therefore an essential component of the present dynamics of our planet. These phenomena could be directly studied by detecting the antineutrinos coming from  $\beta$ -decays of U, Th, K, often called terrestrial antineutrinos, or "geoneutrinos" ( $\bar{\nu}_{geo}$ ).

The recent results from the Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND)<sup>2</sup> experiment have led to a significant progress in neutrino physics. The observed disappearance of reactor antineutrinos is in agreement with the so-called LMA solution of the solar neutrino problem. Alternative oscillation solutions are ruled out with high confidence<sup>3</sup>. Geo-neutrino events from  $^{232}\text{Th}$  and  $^{238}\text{U}$  decays are accessible for the first time in KamLAND (those from  $^{40}\text{K}$  decays are below the experimental threshold for detection), thus opening a new field in geophysics.

Since  $^{232}\text{Th}$  and  $^{238}\text{U}$  antineutrino fluxes in KamLAND are weighted by the inverse squared distance  $1/L^2$ , and since  $^{232}\text{Th}$  and  $^{238}\text{U}$  and  $^{40}\text{K}$  are more abundant in the crust than in the mantle, some input on the relative  $^{232}\text{Th}$ ,  $^{238}\text{U}$  (and  $^{40}\text{K}$ ) abundances in different Earth reservoirs is needed to make sense of future geoneutrino data. The present work illustrates the importance of geochemical studies and inputs, as necessary and useful tools to shed light on what we really know about such abundances and on what we expect to know from  $^{232}\text{Th}$  and  $^{238}\text{U}$   $\bar{\nu}_{geo}$  data. Furthermore, we analyze the impact of KamLAND on the geoneutrino physics. The results can help to improve both the neutrino oscillation analysis, and the knowledge of the Earth interior.

## 2 Geochemical input for data analysis

The usually advertised goal of  $\bar{\nu}_{geo}$  detection is to measure the Earth radiogenic heat. However, even if the  $^{232}\text{Th}$  and  $^{238}\text{U}$  components were known with no error, there would be intrinsic limitations to this goal. We discuss the most important, as follows. First of all, the  $^{40}\text{K}$  component is unmeasurable (in KamLAND) and must be inferred from K/U or K/Th ratios estimates. Actually, the K/U and K/Th bulk ratios are not constrained by meteoritic data, since  $^{40}\text{K}$  is geochemically "volatile", namely its condensation temperature is lower than  $^{232}\text{Th}$  and  $^{238}\text{U}$ . Crust and mantle sampling data, combined with geochemical arguments, are unlikely to reduce the K/U and K/Th ratios uncertainty below, say,  $10 \div 15\%$ <sup>4</sup>, and there might also be a significant amount of potassium (but not  $^{232}\text{Th}$  and  $^{238}\text{U}$ ) in the Earth's core<sup>5</sup>. Finally, the usually quoted Earth's heat flux,  $44 \pm 1$  TW<sup>6</sup> might be severely overestimated by oceanic component systematics and could be as low as  $31 \pm 1$  TW<sup>7</sup>. These uncertainties set intrinsic limitations to the determination of the radiogenic fraction of the Earth's heat flux.

The measure of the  $^{232}\text{Th}$  and  $^{238}\text{U}$  geoneutrino fluxes appears nevertheless useful in geophysics, for the following reasons. Bulk Th/U ratio in the Earth should be close to meteoritic values:  $(\text{Th}/\text{U})_{Earth} = (\text{Th}/\text{U})_{chondritic} \sim 3.8$ . There are no geochemical nor cosmochemical arguments against this guess. However, Th is more easily partitioned than U in melt (i.e. in the crust) than in solid (i.e. in the mantle). Consequently, one expects that:  $(\text{Th}/\text{U})_{Crust} > 3.8$  (probably  $4.5 \div 5.5$ ),  $(\text{Th}/\text{U})_{Mantle} < 3.8$  (probably  $2 \div 3$ ). These expectations are confirmed by geochemical measurements in the crust and in the upper mantle. Since geoneutrino experiments (including KamLAND) are dominated by the crust contribution, they should then observe  $(\text{Th}/\text{U})_{Crust-dominated} > 3.8$ . Combining this datum with Crust and upper Mantle sampling, mass balance arguments<sup>8</sup> can be used to evaluate the  $(\text{Th}/\text{U})_{Lower-Mantle}$  ratio. Therefore, we might infer mantle layering if  $(\text{Th}/\text{U})_{Lower-Mantle}$  is different from  $(\text{Th}/\text{U})_{Upper-Mantle}$ .

We analyze, now, how to attach errors to the  $^{232}\text{Th}$  and  $^{238}\text{U}$  abundance estimates. One

possible approach<sup>1</sup> is to evaluate central values and errors from spread of published  $^{232}\text{Th}$  and  $^{238}\text{U}$  estimates (e.g., attach  $\pm 3\sigma$  significance to extremal values). This approach is good as a first guess, but is also affected by some limitations: 1) the published estimates are often "duplicates" (i.e., they depend on each other); 2) without a criterion to discard obsolete estimates or unreliable outliers, no progress is possible in reducing errors. As consequence, there is no way out than carefully sifting the available geo-literature, identifying virtues and problems of each estimate, selecting the more reliable and complete ones, and evaluating from scratch the uncertainties. Error evaluation is not as common practice in geo-sciences as it is in particle physics, unfortunately.

Only recently (2003) a geochemical Earth model has appeared, in which input uncertainties are well defined (although questionable in size) and propagated to output element abundances<sup>9</sup> through standard statistical techniques. The corresponding Th and U estimates for the Bulk Silicate Earth (mantle plus crust) at  $1\sigma$  can be expressed as:

$$[\text{Th}] = 83.5 (1\pm 0.12) \text{ ppb}, \\ [\text{U}] = 21.9 (1\pm 0.12) \text{ ppb},$$

with correlation  $\rho = 0.38$  (our provisional estimate). Consequently, we obtain the following ratio:

$$\text{Th}/\text{U} \simeq 3.8 (1\pm 0.14) \quad (\text{for bulk Earth}).$$

This estimate can be refined through a more careful use of meteoritic (chondritic) data. This is an important task since  $(\text{Th}/\text{U})_{\text{Earth}}$  plays a pivotal role in Mantle-Crust balances. In fact, the value of  $(\text{Th}/\text{U})_{\text{Crust}} > (\text{Th}/\text{U})_{\text{Earth}}$  (testable by KamLAND) might be used to evaluate if  $(\text{Th}/\text{U})_{\text{Mantle}} < (\text{Th}/\text{U})_{\text{Earth}}$ . As emphasized before, this is a potential tool to test the difference between upper mantle and lower mantle. This information must be folded with careful estimates of (Th/U) variations, both vertical (crust layers and mantle layers) and horizontal (crust types).

In principle, large amounts of data and constraints are available, but dedicated global studies are still lacking. Interaction with geo-science community would be beneficial.

### 3 Desiderata for KamLAND Data Analysis

In this section, we analyze the information coming from the KamLAND experiment and comment on its role in future geo-neutrino data analysis. A model-independent check that, e.g., the Th/U ratio in the crust is greater than the chondritic value, requires that Th and U component are left free in the analysis. The current (binned) data can give only very weak constraints, of course. Since the statistics will be very low for quite some time, it is wise to use as much information as possible. So, it would be useful to avoid the binning procedure, and tag each single event in energy (recoverable from the current KamLAND plots).

Fig. 1 (upper panel) shows the iso-contours at 95% C.L. in a four-parameters analysis, projected onto the plane charted by the U and Th number of  $\bar{\nu}_{\text{geo}}$  events in KamLAND. The figure shows the comparison between Least-Squares (binned) and Likelihood (unbinned) analysis. It appears that unbinned analysis of KamLAND data (through maximum likelihood) yields tighter constraints on Th and U contributions. The loss of information implied by the binning of the data is non-negligible, and the likelihood analysis provides a more powerful method to extract information from the KamLAND data. We conclude that it should be used as a default. So, the first desideratum is that the KamLAND collaboration should provide the energies of each event. We notice, as also shown in<sup>10</sup>, that unbinned analyses provide better constraints not only on Th and U contributions but even on the oscillation parameters, as shown in Figure 1 (lower panel).

A further and equally important requirement, is to use time information. The geo-neutrino flux is constant, while the flux coming from reactors follows seasonal and/or occasional variations due to possible reactors' shut-downs (known to KamLAND Collaboration). Fig. 2 shows the

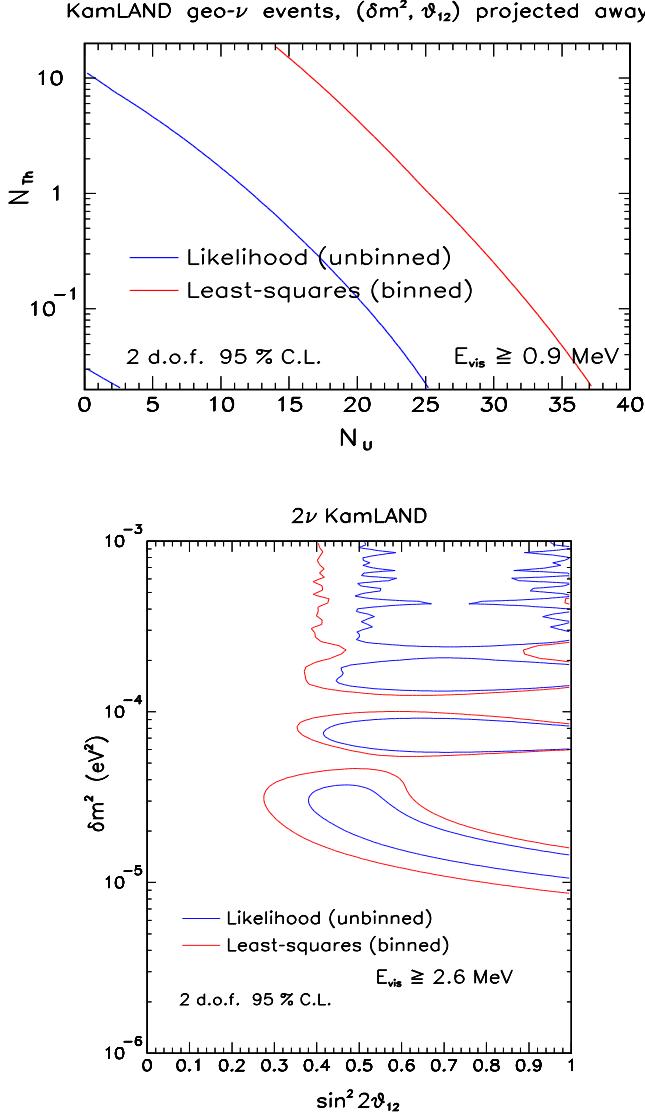


Figure 1: Upper Panel: comparison of the 95% C.L. regions obtained from the Likelihood analysis with the regions obtained from the Least-Squares analysis, projected onto the plane of U and Th number of events. Lower-Panel: comparison of the 95% C.L. regions obtained from the Likelihood analysis with the regions obtained from the Least-Squares analysis in the oscillation parameter space.

constant geoneutrino signal, superimposed to the variable reactor signal. It can be seen that typical time variations of the reactor signal can be as large as the contribution from  $\bar{\nu}_{geo}$ . This is an additional handle to separate the constant geo-neutrino contribution from the variable reactor signal<sup>11</sup>, if an unbinned energy-time maximum likelihood is used. As Figure 2 shows, the main variation of the reactor signal corresponds to the U tail in the geoneutrino spectrum. Therefore, future data analyses with possibly lower experimental threshold would be useful to evaluate the U component, and to discriminate U and Th contribution in the total geoneutrino flux. The second desideratum is thus that, for each KamLAND event, energy plus time information should be released, and the reactors flux history should also be provided.

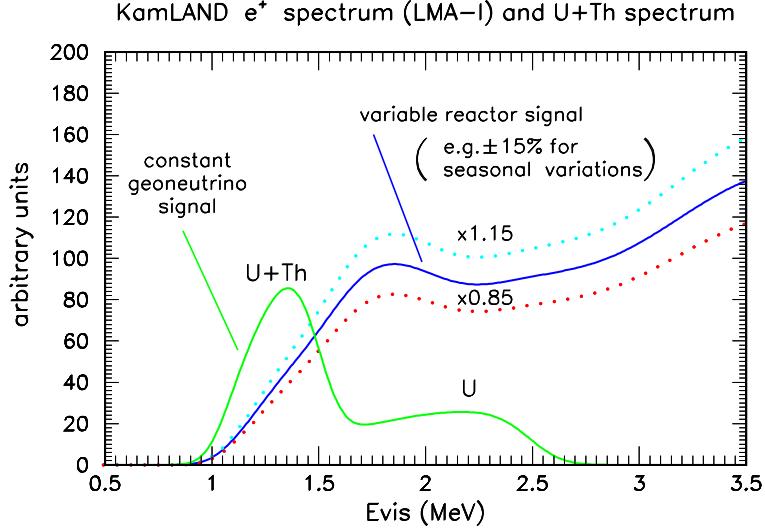


Figure 2: KamLAND positron spectrum (LMA-I) and geoneutrino spectrum (U and Th). The figure shows possible time variations (e.g.  $\pm 15\%$  for seasonal variation) of the reactor component, and the time-independent trend of the geo-neutrino component.

#### 4 Future Prospects

Concerning the future, the list of the desiderata must certainly include new experiments in geophysically different sites such as: Borexino, LENA, Sudbury, Hawaii, Baksan.

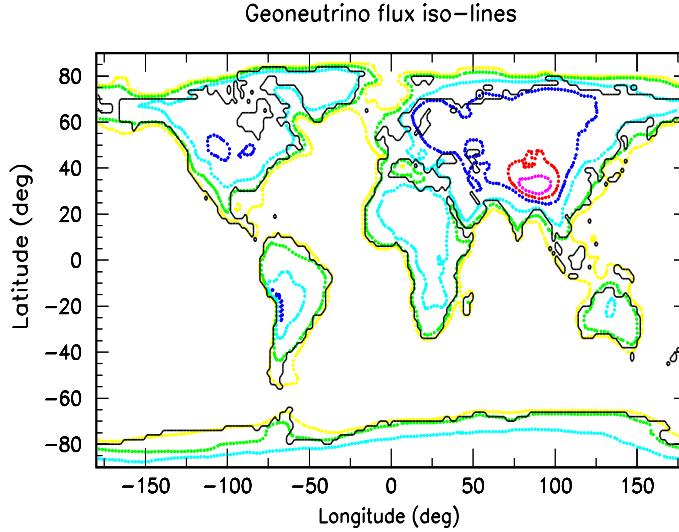


Figure 3: Geoneutrino flux iso-lines.

A network of detectors located in different points of the Earth would be useful to obtain a complete and precise information about the different contribution to the anti-neutrino fluxes. In fact, detectors located in continental crust zones would give information on the dominant crust contribution, while detectors placed in oceanic crust zones would help to measure the upper mantle contribution. Fig. 3 shows geoneutrino flux iso-lines with lowest fluxes in oceanic zones and highest peaks at thick continental zones (e.g., the Himalaya chain). Several experiments are also needed to average out local uncertainties in Th and U distributions, as explained in<sup>12</sup>.

## 5 Conclusions

The KamLAND experiment will start a new field of geo-neutrino observations, and might be followed by other similar experiments. Large uncertainties might hide the underlying (geo-) physics for quite some time, but steady progress can be envisaged, if the particle physics and the geophysics communities identify common goals. In particular: 1) An effort can and should be made to characterize the geophysical and geochemical input in “particle physics language”: central values, errors and correlations, e.g. on Th/U ratio. Missing input should be identified and worked out by the two communities. 2) The few geo-neutrino events which will be collected by KamLAND (and possibly other experiments) in the future deserve our best analysis tools, to squeeze the maximum amount of information. Time and energy tagging of each individual event can help to discriminate the geo-neutrino signal from the reactor component. Full publicity and full information of single events and single reactor history is essential to achieve this goal.

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## References

1. F. Mantovani, L. Carmignani, G. Fiorentini, M. Lissia, *Phys. Rev. D* **69**, 013001 (2004)
2. KamLAND Collaboration, K. Eguchi, et al., *Phys. Rev. Lett.* **90**, 021802 (2003).
3. G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno, *Phys. Rev. D* **67**, 073002 (2003).
4. K.P. Jochum, A.W. Hofmann, E. Ito, H.M. Seufert, W.M. White, *Nature* **306**, 431 (1983).
5. V. Rama Murthy, W. Van Westrenen, Y. Fei *Nature* **423**, 163 (2003); Lee and Jeanloz, *Geophys. Rev. Lett.* **30**, 2212 (2003).
6. H.N. Pollack, J.R. Johnson, *Geophys. Rev. Lett.* **31**, 267 (1993).
7. Hofmeister and Criss, preprint submitted to *Tectonophysics*.
8. D.L. Turcotte et al., *J. of Geophys. Res.* **106**, 4265 (2001).
9. H. Palme, H. O'Neill, *Treatise on Geochemistry*, Elsevier, (2003).
10. T. Schwetz, *Phys. Lett. B* **577**, 120 (2003).
11. E. Lisi, A. Palazzo, A.M. Rotunno, hep-ph/0403036.
12. G.L. Fogli, E. Lisi, A. Palazzo, A.M. Rotunno, work in progress.